THE SEMANTIC CONCEPTION OF PROOF

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1.

Classically, the notions of truth and provability are both directly tied to the meanings of the logical constants. The typical setting involves a model M and a language L which is to be interpreted in M. The informational content of L is determined by the way we specify which sentences of L are true. Fixing an interpretation, the usual way to do this is to begin by defining a function from the atomic formulas of L into the set $\{\mathrm{true}, \mathrm{false}\}$ in some way that reflects the structure of M. We then extend this function to complex formulas recursively by means of truth conditions (e.g., $A \wedge B$ is true iff A is true and B is true). This is the classical account of the role of truth in specifying the meanings of the logical constants.

We also have a notion of deductive reasoning as the means by which we come to know which sentences are true. Proofs typically proceed though a series of inferences which conform to certain deduction rules. (Throughout this paper we restrict attention to proofs of finite length.) These rules can be formulated in terms very similar to the truth conditions, in a way that also transparently reflects the meanings of the logical constants (e.g., given A and B one may infer $A \wedge B$, and given $A \wedge B$ one may infer both A and B) [2]. It is easy to see that deductions preserve truth, so that any proof which proceeds from axioms which are true in the model will establish a conclusion which is also true in the model. Thus anything which is provable should be true, but there is no reason to expect the converse to hold in general.

However, this implication (provable implies true) can only be affirmed for formal proofs relative to some system of axioms which are known to be true. It is a weakness of the classical picture that we do not have a general account of how we are to go about choosing the axioms on which we base our proofs. The seriousness of this problem can already be seen in the case of first order number theory, where it is generally accepted that the usual Peano axioms, for instance, do not exhaust our knowledge of what is true in the model. Indeed, because the true sentences of first order arithmetic are not recursively enumerable, we will always have the capacity to strengthen any recursively presented formal system for number theory that is known to be sound by adding a (standardly expressed arithmetical) statement of its consistency. This consistency statement cannot have been formally provable in the original system, but if we can see that that system is sound then its consistency is certainly provable in an informal semantic sense. And if we do not recognize that the original system is sound, then the formal proofs of that system clearly cannot function as genuine proofs in a semantic sense. So in neither case do the formal proofs of the given system adequately express the semantic concept of a valid proof.

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These considerations suggest that the semantic notion of a valid proof as a linguistic object which compels rational assent is not so easy to formally capture.

The subtlety of the semantic notion of a valid proof, in contrast to the straightforwardness of the syntactic notion of a valid proof within a formal system, might lead us to focus on the latter at the expense of the former. But we should not lose sight of the fact that the main reason we care about formal proofs is because we think they exhibit semantic validity.

2.

The classical picture outlined above is unsuited to cases where we are not able to affirm that every atomic formula of the language has a well-defined truth value in the model (relative to a given interpretation). There are various ways this can happen. For instance, the recursive enumerability issue mentioned above makes it doubtful that the assertion "A is provable", in the sense of semantic provability (and restricting to proofs of finite length), can be said to have a definite truth value for every sentence A of first order number theory.

Actually, once we are in the business of explicitly reasoning about semantic provability, there is no need to invoke Gödelian incompleteness to make this point. It is easy to see directly how assigning a truth value to a sentence that asserts the soundness of some deduction rule could be problematic. For in order to do this we would need to know whether the rule preserves truth, but that would depend on which sentences are true, and could potentially hinge on the truth value of the sentence under consideration. A vicious circle is possible.

Thus, when we are reasoning about provability, we cannot necessarily assume that every atomic proposition has a definite truth value. This creates difficulties for the interpretation of the logical constants; we can no longer characterize them in terms of truth conditions. The constructivist solution to this sort of problem is to take the deduction rules, rather than the truth conditions, as our starting point. This is possible because the deduction rules, despite intuitively having essentially the same content as the truth conditions, are nonetheless formulated without reference to truth values. Thus, classically, we use truth conditions to give meaning to the logical constants, and we justify the deduction rules by observing that they preserve truth, but constructively, we discard the truth conditions, regard provability as primary, and use the deduction rules to give meaning to the logical constants. The rules for $\wedge$ tell us what $\wedge$ means in the sense that they tell us under what circumstances we are entitled to assert $A \wedge B$: we are entitled to assert $A \wedge B$ precisely if we are entitled to assert both A and B. This approach gives us a way to reason about formulas that might not have definite truth values.

An unfortunate byproduct of this emphasis on provability is that constructivists are not always careful about distinguishing between a statement and the assertion that that statement is provable.[1] The two are not synonymous. That we can prove there are infinitely many primes is indeed what licenses us to assert there are infinitely many primes, and we can arguably regard the meaning of the assertion that there are infinitely many primes as residing in our characterization of what constitutes a proof of this assertion, but saying there are infinitely many primes is

[1] E.g., "The assertion of $A \vee \neg A$ is therefore a claim to have, or to be able to find, a proof or disproof of A" ([1], p. 21). More correct would be "We are entitled to assert $A \vee \neg A$ if we have, or are able to find, a proof or disproof of A."

not the same as saying we can prove there are infinitely many primes. One is a statement about numbers, the other a statement about proofs. For our purposes here, preserving this distinction is absolutely crucial.

3.

We take a proof to be a syntactic object — not a "procedure" or a "construction" — that compels rational acceptance of some conclusion. We consider the proof relation to be a primitive notion that cannot be defined in any simpler terms. The most basic feature of a valid proof, in this conception, is that it must be recognizably valid. That is, if p proves A then we must in principle be able to recognize that p proves A. This is inherent in what we mean by a proof. If we cannot see that p compels us to accept A, then we do not consider p to be a proof of A in the semantic sense of concern to us here.

It is not important for us whether proofs are expressed linearly or as trees (or in some other way), just that they be finite syntactic objects. We assume only that we have a notion of one proof being contained within another and that for any two proofs there is a third that contains both of them. Also, we will allow proofs to contain extraneous material. It is not clear how a prohibition on inessential content could be formulated, but even if it could, doing so would be inconvenient for us. Therefore we stipulate that if p proves A then p' also proves A, for any proof p' containing p.

We now want to work out how the meanings of the various logical constants can be expressed in terms of the proof relation. For instance, we take a proof of $A \vee B$ to be something which is either a proof of A or a proof of B. Thus p proves $A \vee B$ if and only if p proves A or p proves B. Similarly, a proof of $A \wedge B$ is something which is both a proof of A and a proof of B. (Allowing proofs to contain extraneous material simplifies things here; a proof of $A \wedge B$ does not have to be a pair of proofs, it can simply be a proof that contains both a proof of A and a proof of B.) So p proves $A \wedge B$ if and only if p proves A and p proves B.

A proof of $(\exists x)A(x)$ is something which proves $A(t)$ for some term t. Since it is a name for an object, not the object itself, that appears in the assertion A, in order to give a proof interpretation of existential quantification we need to require that every individual in the model be represented by a term in the language. This can always be assured by simply including a constant symbol in the language for each individual in the model. (Cf. the need to represent abstract objects by concrete proxies, discussed in Section 3 of [4].)

Our accounts of $(\forall x)A(x)$ and $A \to B$ require a more detailed explanation. In the traditional literature their proof interpretations are framed in terms of "constructions": we ask for a construction which, for each x, produces a proof of $A(x)$, or a construction which converts any proof of A into a proof of B. This kind of formulation is implausible on its face. For example, consider a computer program that inputs natural numbers x, y, z, and n, and then, if $n \geq 3$, prints out a step-by-step evaluation of both $x^n + y^n$ and z^n and a verification that they are unequal (say, by comparing them digit by digit). Since Fermat's last theorem is true, it follows that this procedure does in fact convert any quadruple (x, y, z, n) such that $n \geq 3$ into a proof that $x^n + y^n \neq z^n$. So according to the definition just mentioned, this trivial procedure would count as a proof of Fermat's last theorem.

We might consider adding a clause to the effect that the procedure must not only produce a proof of $A(x)$ for each x, but also be recognized to do so. (In fact, it is clear that we have to do this if we are to sustain our requirement that any proof can be recognized to be a proof.) The problem here is that recognizing that it is possible to generate a proof of $A(x)$ is not the same as being compelled to accept $A(x)$. It is, rather, the same as being compelled to accept that $A(x)$ is provable. This is just the distinction we emphasized earlier between asserting some statement and asserting that that statement is provable. There really is no way to maintain it here because it is essential to the construction viewpoint that one does not actually have a proof of $A(x)$ for every x, one only has a way of generating these proofs.

This issue might be confusing because of the condition that any valid proof must be recognizably valid. It follows from this condition that if p proves A then it not only compels acceptance of A, it must also compel acceptance of the fact that it proves A. This means that any proof of $(\forall x)A(x)$ would actually also prove that $A(x)$ is provable for every x. But it is the converse implication (going from "$A(x)$ is provable" to $A(x)$) that would be needed to justify the construction interpretation.

The only thing we can do is to define a proof of $(\forall x)A(x)$ to be a single argument p which, for every term t, compels us to accept the statement $A(t)$. Now, it is natural to object that demanding a uniform proof of $A(x)$ is too restrictive. The concern is that it might be possible to, in some uniform way, generate proofs of $A(x)$ for various values of x without being able to give a single finite proof that simultaneously covers all cases. But this objection is not well-taken. Not only does it, as we have just explained, ignore the distinction between proving $A(x)$ and proving that $A(x)$ is provable, it also fails on its own terms. For suppose we had a construction that produced a proof of $A(x)$ for every x. How could we know that it did this? If there are infinitely many possible values of x then direct inspection is not an option. But asking the construction to be accompanied by a collection of proofs, one for each x, that it produces a proof of $A(x)$ would be absurd; if we allowed that then we could just as well discard the construction altogether and simply ask for a collection of proofs of $A(x)$, one for each x. On the other hand, demanding a single, uniform, finite proof that the construction produces a proof of $A(x)$ for every x negates the original basis of the objection. Any approach at some point has to come down to a single finite proof; all the construction viewpoint accomplishes is to erase the distinction between a statement and the assertion that that statement is provable.

Similar comments apply to implication. Again, to prove $A \to B$ it is not enough to know that we can use any proof of A to generate a proof of B; if anything, that would establish that A is provable implies B is provable, not that A implies B. The proper formulation is that a proof of $A \to B$ is an argument that, granting A, compels rational acceptance of B. We can say that p proves $A \to B$ if and only if p' proves A implies p' proves B, where p' ranges over proofs which contain p.

This completes our informal explication of the logical constants in terms of provability. Negation is handled by taking $\neg A$ to be an abbreviation of $A \to \perp$, where $\perp$ represents some canonical falsehood.

We can also reason about the proof relation itself. We mentioned above that if p proves A then p also proves that p proves A, but we warned against assuming the converse implication. It is certainly the case that whenever we have proven a statement we accept that statement. However, we cannot take this implication as

an axiom because of the possible circularity involved in its application to proofs in which it appears. It can only be formulated as a deduction rule: given that p proves A, infer A. We will elaborate on this point below.

Now that we have an account of the logical constants, we can restate the principles given above in terms of them. This will allow us to treat the proof relation formally. We write $p \vdash A$ for "p proves A". The axioms for the proof relation are then

$$\begin{array}{rcl}
p \vdash A & \to & p' \vdash A \\
p \vdash (A \vee B) & \leftrightarrow & (p \vdash A) \quad \vee \quad (p \vdash B) \\
p \vdash (A \wedge B) & \leftrightarrow & (p \vdash A) \quad \wedge \quad (p \vdash B) \\
p \vdash (\exists x)A & \leftrightarrow & (\exists x)(p \vdash A) \\
p \vdash (\forall x)A & \leftrightarrow & (\forall x)(p \vdash A) \\
p \vdash (A \to B) & \leftrightarrow & (p' \vdash A \quad \to \quad p' \vdash B) \\
p \vdash A & \to & p \vdash (p \vdash A)
\end{array}$$

and we have a deduction rule which infers A from $p \vdash A$. As always, p' ranges over all proofs which contain p.

In each of the biconditionals listed above, a proof of either side would literally also be a proof of the other side. For instance, a proof that p proves $(\forall x)A$ is a proof that p proves $A(t)$ for every term t; and that is also what a proof of $(\forall x)(p \vdash A)$ is. For the first displayed axiom, we consider any proof that p proves A to also be a proof that p' proves A, for any p' containing p, and likewise for the last axiom. Thus the empty proof proves each of the axioms listed above.

The proof interpretation of the logical constants presented in this section immediately justifies the usual axioms and rules of minimal first order predicate calculus. (In particular, the empty proof proves every tautology.) Thus we are now free to reason accordingly. To recover intuitionistic logic in some setting we would need to give a special justification for the ex falso quodlibet law, and to recover classical logic we would also need to give a special justification for the law of excluded middle.

4.

To assert that A is provable is to assert that there exists a proof of A. Formally, we define $\Box A$ to mean $(\exists p)(p \vdash A)$. Basic laws relating provability to the logical constants can now be derived from the axioms given in the last section. For instance, if $A \vee B$ is provable then there exists a proof p of $A \vee B$, and this p is either a proof of A or a proof of B, so that we have shown that either A or B is provable. Thus we see that $\Box(A \vee B)$ implies $\Box A \vee \Box B$ in general. Conversely, if either A or B has a proof then that proof is also a proof of $A \vee B$, which shows that $\Box A \vee \Box B$ implies $\Box(A \vee B)$. We conclude that $\Box(A \vee B)$ and $\Box A \vee \Box B$ are equivalent. The equivalence of $\Box(A \wedge B)$ and $\Box A \wedge \Box B$ can be seen in a similar way, this time using the property that if p proves A and q proves B, then any proof containing both p and q proves both A and B.

If $(\exists x)A$ is provable then there exist p and x such that p proves $A(x)$. Thus, there exists x such that $A(x)$ is provable. Conversely, if there exists x such that $A(x)$ is provable then there exist x and p such that p proves $A(x)$, i.e., $(\exists x)A$ is provable. So $\Box(\exists x)A$ is equivalent to $(\exists x)\Box A$.

Similarly, $\Box(\forall x)A$ implies $(\forall x)\Box A$, but in this case the converse direction cannot be deduced from the laws for $\vdash$ stated in the last section. However, we can still argue for the converse in the following way. Any proof p of $(\forall x)\Box A$ must be a proof of $\Box A(x)$ for every x. That is, for every x there is a proof term t_i such that p proves $t_i \vdash A(x)$. Different terms might be involved depending on the value of x, but since p is finite the worst that can happen is that it contains finitely many proof terms $t_1, \ldots, t_n$ and proves, for every x, that one of them proves $A(x)$. Letting t be a proof term that contains each t_i, we then have that p proves $t \vdash A(x)$ for all x. Thus p proves $\Box(\forall x)A$. So we conclude that $(\forall x)\Box A$ also implies $\Box(\forall x)A$.

(The preceding argument is noteworthy because n is arbitrary, which means that we need to use induction to establish the existence of the term t. Thus, some simple number theoretic reasoning is needed in order to see that any proof of $(\forall x)\Box A$ is also a proof of $\Box(\forall x)A$. This example shows that there can be cases where it is not immediately obvious that something is a proof, but after some reflection, we can see that it is.)

For implication, suppose $A \to B$ is provable. Then some p proves $A \to B$, i.e., p' proves A implies p' proves B for any proof p' containing p. Together with the premise that A is provable, this yields that B is provable, since any proof of A can be combined with p to produce a proof of B. So we have shown that $\Box(A \to B)$ implies $\Box A \to \Box B$. The converse is not evident.

We also consider the general relationship between A and $\Box A$. Recall that if p proves A then p proves that p proves A. This yields that the empty proof is always a proof of $A \to \Box A$. For whenever any p is a proof of the premise, i.e., $p \vdash A$, it follows that p is a proof of $p \vdash A$ and hence of $\Box A$. The converse is not evident. For suppose that A is provable, i.e., some p proves A. To infer A from this premise we would need to use the law $\Box A \to A$ which we are trying to prove. There is no obvious way around this circularity. We can only affirm the deduction rule: given $\Box A$, infer A.

To summarize, we have the axioms

$$\begin{array}{rcl}
\Box(A \vee B) & \leftrightarrow & \Box A \vee \Box B \\
\Box(A \wedge B) & \leftrightarrow & \Box A \wedge \Box B \\
\Box(\exists x)A & \leftrightarrow & (\exists x)\Box A \\
\Box(\forall x)A & \leftrightarrow & (\forall x)\Box A \\
\Box(A \to B) & \to & (\Box A \to \Box B) \\
A & \to & \Box A
\end{array}$$

and the deduction rule that infers A from $\Box A$.

5.

The most important conclusion we reached in the last section is that we do not have a right to affirm the law $\Box A \to A$ in general. This may be counterintuitive because it seems as though having a proof that there is a proof of A should be just as good as having a proof of A. Once we have accepted a line of reasoning which establishes that p proves A we ought to then accept p as a proof of A. The problem is the circularity that arises when we try to affirm this inference as a general principle. It becomes circular when it is adopted as a universal law because it then has the effect of affirming the soundness of proofs in which it might itself have been used.

The situation is analogous to the difficulty associated with formal systems that prove their own consistency. Once we have accepted a formal system $\mathcal{S}$ we do generally agree to accept a stronger system $\mathcal{S}'$ obtained by augmenting $\mathcal{S}$ with a (standardly expressed arithmetical) assertion of the consistency of $\mathcal{S}$. However, the new consistency axiom is only applied in retrospect, to affirm the correctness of reasoning which could be executed in the original system $\mathcal{S}$. We should not accept a new axiom which expresses the consistency not of the original system, but of the new system formed by adjoining that axiom itself. That would be circular, and we know from Gödel's second incompleteness theorem that it is not a benign sort of circularity; any such axiom would have to give rise to an inconsistency. In just the same way, once we accept some formal system we should agree, whenever that system proves that A is provable, to accept A; but we should not agree to vouch for the original system augmented by the axiom $\Box A \to A$. Adding the latter axiom would affirm the soundness not just of all proofs in the original system, but also of all proofs in the augmented system, including proofs that employ the new axiom itself.

Maintaining a distinction between A and $\Box A$ is essential for properly handling the semantic paradoxes involving provability [5]. Most importantly, given that some statement L entails that a contradiction is provable, i.e., $L \to \Box\bot$, we cannot infer that L is false, i.e., $L \to \bot$. Since we do have $\bot \to \Box\bot$ as a special case of the law $A \to \Box A$, an inference can be drawn in the opposite direction: given $L \to \bot$ we may deduce $L \to \Box\bot$. In this sense the assertion $L \to \bot$, which is the standard negation of L, is stronger than the assertion $L \to \Box\bot$. We call $L \to \Box\bot$ the *weak negation* of L and when we have proven this we say that L is *weakly false*.

The semantic paradoxes involving provability collapse when we are careful to distinguish a statement from the assertion that that statement is provable. For instance, let L be a sentence which asserts that its negation is provable. Assuming L, we can then immediately infer $\Box\neg L$. We can also infer $\Box L$ from L, as an instance of the general law $A \to \Box A$. Putting these together yields $L \to \Box\bot$, i.e., L is weakly false. Taking $\neg L$ as a premise instead allows us to infer $\Box\neg L$, which is equivalent to L, and this shows that $\neg L$ is false. So the conclusion we reach is that L is weakly false and $\neg L$ is false. But there is no contradiction here.

In this example the distinction between falsity and weak falsity is crucial. If the two were equivalent then we would have proven both $\neg L$ and $\neg\neg L$, which is absurd. What this means is that it is not merely the case that we cannot affirm the implication $\Box\bot \to \bot$. Since this implication would imply that falsity is equivalent to weak falsity, it would, together with the preceding analysis of L, yield a contradiction. In other words, we have shown $(\Box\bot \to \bot) \to \bot$, which can also be written as $\neg(\Box\bot \to \bot)$ or as $\neg\neg\Box\bot$. Thus, in the case where A equals $\bot$, we can affirm that the law $\Box A \to A$ is false.

This conclusion would be unacceptable if we were to interpret implication classically. According to the classical interpretation, the only way an implication can fail is if the premise is true and the conclusion is false; so the law $\Box\bot \to \bot$ could only fail if $\bot$ were actually provable. But then, if we were reasoning classically we could apply the law of excluded middle to L and infer $\Box\bot$ from the fact that both L and $\neg L$ are weakly false. So in fact we could actually prove $\Box\bot$.

This only confirms our earlier judgement that it is inappropriate to reason about provability classically. Indeed, liar type sentences are just the sort of thing that

show us we may not always be in a position to assign definite truth values to assertions about provability. So we have to reason constructively, and affirming that $\Box\bot \to \bot$ is false is perfectly reasonable under a constructive interpretation of implication. It merely expresses the idea that if we could find some way of converting any (hypothetical) proof that a falsehood is provable into a proof of a falsehood, then a contradiction would result. In simpler language, assuming that $\bot$ is unprovable leads to a contradiction. As we explained above, this assumption is indeed unwarranted because it hinges on the global soundness of all proofs, and any proof whose soundness is justified by invoking the global soundness of all proofs is a proof whose justification is circular.

Here too there is an analogy with the Gödelian analysis of consistency in number theoretic systems. We can prove, in Peano arithmetic, that if PA proves Con(PA) then PA proves $0 = 1$. Since Con(PA) is just the statement that $0 = 1$ is not provable in PA, this amounts to saying that assuming PA proves that $0 = 1$ is unprovable in PA leads to a contradiction in PA. This mirrors our conclusion that assuming $\bot$ is unprovable leads to a contradiction.

6.

In the last section we showed how a certain liar type sentence narrowly avoids paradox. This happens because we lack both the law $\Box A \to A$ (otherwise we could prove $\bot$) and the law of excluded middle (otherwise we could prove $\Box\bot$, and then infer $\bot$). We now want to prove in a formal setting that the kind of reasoning exhibited above actually is consistent, even when dealing with circular phenomena.

We formulate a propositional system $\mathcal{P}$ for reasoning about assertions which reference each other's provability in a possibly circular way. The atomic formulas of the language consist of the falsehood symbol $\bot$ together with finitely many propositional variables $\phi_1, \ldots, \phi_n$. Complex formulas are generated from the atomic formulas by the rule that whenever A and B are formulas, so are $A \wedge B$, $A \vee B$, $A \to B$, and $\Box A$.

The logical axioms and rules of $\mathcal{P}$ are those of a minimal propositional calculus, together with the axioms and rule for $\Box$ presented in Section 4 (minus the two axioms for quantification).

The nonlogical axioms of $\mathcal{P}$ will consist of a list of formulas $\phi_1 \leftrightarrow A_1$, $\ldots$, $\phi_n \leftrightarrow A_n$, where each A_i can be any formula in which every propositional variable lies within the scope of some box operator. Thus $\phi_1 \leftrightarrow \neg\Box\phi_1$ and $\phi_2 \leftrightarrow \Box\neg\phi_2$ are acceptable axioms but $\phi_3 \leftrightarrow \neg\phi_3$ is not. The list might include liar pairs such as $\phi_4 \leftrightarrow \Box\phi_5$ and $\phi_5 \leftrightarrow \neg\Box\phi_4$. The restriction on the A_i's arises from the grammatical distinction between asserting a proposition and merely mentioning its name. "The negation of ϕ_3" is not a cogent assertion; we have to say something like "ϕ_1 is not provable" or "the negation of ϕ_2 is provable".

It is easy to show that $\mathcal{P}$ minus the rule which infers A from $\Box A$ is consistent: just make $\Box A$ true for every formula A and evaluate the truth of the ϕ_i and all remaining formulas classically; then the set of true formulas contains all the theorems of $\mathcal{P}$ but does not contain $\bot$. Proving that $\Box^k\bot$ is not a theorem of this system for any k is a little more substantial.

Theorem 6.1. *$\mathcal{P}$ is consistent.*

Proof. We define the level $l(A)$ of a formula A of $\mathcal{P}$ as follows. The level of $\perp$ and any formula of the form $\Box A$ is 1. The level of $A \wedge B$, $A \vee B$, and $A \to B$ is $\max(l(A), l(B)) + 1$. The level of ϕ_i is $l(A_i) + 1$.

Now we define a sequence of sets of formulas $F_1, F_2, \ldots$. These can be thought of as the formulas which we have determined not to accept as true. The definition of F_k proceeds by induction on level. When $k = 1$, the formula $\perp$ belongs to F_1 but no other formula of level 1 belongs to F_1. For $k > 1$, $\perp$ belongs to F_k and $\Box A$ belongs to F_k for every formula A which belongs to F_{k-1}. For levels higher than 1, we apply the following rules. If either A or B belongs to F_k then $A \wedge B$ belongs to F_k. If both A and B belong to F_k then $A \vee B$ belongs to F_k. If A_i belongs to F_k then ϕ_i belongs to F_k. Finally, if there exists $j \leq k$ such that B belongs to F_j but A does not belong to F_j, then $A \to B$ belongs to F_k.

An easy induction shows that the sequence (F_k) is increasing. We define $F = \bigcup F_k$. It is obvious that $\perp$ belongs to F. The proof is completed by checking that none of the axioms of $\mathcal{P}$ belongs to F, and that the complement of F is stable under modus ponens and the inference of A from $\Box A$. This is tedious but straightforward. $\Box$

An identical argument would prove the consistency of a stronger system with the box axiom for implication strengthened to $\Box(A \to B) \leftrightarrow (\Box A \to \Box B)$ and minimal logic strengthened to intuitionistic logic. However, the justification for these stronger axioms is unclear. In particular, there is no obvious way of defining $\perp$ so as to justify the ex falso law in this setting. Since $\perp$ could appear in the defining formulas for the ϕ_i, a circularity issue arises if we try to build the implications $\perp \to \phi_i$ into the definition of $\perp$.

7.

Taking $\phi \leftrightarrow \neg\phi$ as an axiom guarantees inconsistency, but as we have just seen, $\phi \leftrightarrow \neg\Box\phi$ does not. Thus, inserting box operators into the axioms of an inconsistent theory can sometimes make it consistent. We now want to describe a general technique for proving results of the opposite type which state that in some cases inserting box operators into axioms does not essentially weaken them.

Let $\mathcal{T}_1$ and $\mathcal{T}_2$ be formal systems based on the same underlying logic (classical, intuitionistic, or minimal), such that the language of $\mathcal{T}_2$ is the language of $\mathcal{T}_1$ augmented with $\Box$. Also assume that the axioms and deduction rule for $\Box$ are included in the theory $\mathcal{T}_2$. Then we say that $\mathcal{T}_2$ *weakly interprets* $\mathcal{T}_1$ if, when all appearances of $\Box$ are deleted from the theorems of $\mathcal{T}_2$, the resulting set of formulas contains all the theorems of $\mathcal{T}_1$. Informally, $\mathcal{T}_2$ weakly interprets $\mathcal{T}_1$ if $\mathcal{T}_2$ interprets $\mathcal{T}_1$ when we ignore the difference between A and $\Box A$. We have the following trivial result:

Proposition 7.1. *If $\mathcal{T}_2$ weakly interprets $\mathcal{T}_1$ then the consistency of $\mathcal{T}_2$ implies the consistency of $\mathcal{T}_1$.*

This is just because if $\mathcal{T}_1$ were inconsistent then $\perp$ would be a theorem of $\mathcal{T}_1$, and weak interpretability then implies that $\Box^k\perp$ must be a theorem of $\mathcal{T}_2$ for some k. Repeated application of the rule "infer A from $\Box A$" then shows that $\perp$ is a theorem of $\mathcal{T}_2$.

We will now describe a procedure for inserting box operators into formulas that lack them and prove that if the initially given formula is a theorem of a standard (classical, intuitionistic, or minimal) predicate calculus then we can ensure that

the formula generated by our procedure will be a theorem of that predicate calculus augmented by the axioms for $\Box$. This result can be used to establish weak interpretability results; we illustrate this in the corollary below.

Our procedure can be described as a game between two players, Attacker and Defender, on a formula A. We think of Attacker as seeking to strengthen the formula and Defender as seeking to weaken it. The way the game is played is defined inductively on the complexity of A. If A is atomic then the game consists of a single move in which Defender chooses a value of k (possibly zero) and prefixes A with $\Box^k$. Attacker does not have a turn. The game is played on formulas of the form $A \wedge B$ by independently playing the game on A and B and conjoining the results. It is played on $A \vee B$ by independently playing on A and B and disjoining the results. It is played on $(\exists x)A$ and $(\forall x)A$ by playing on A and prefixing the result with the relevant quantifier. Finally, it is played on $A \to B$ by first having the players switch roles and play on A, producing a formula A', then revert to their original roles and play on B, producing a formula B'. The result of this game is the formula $A' \to B'$.

If the initially given formula is a theorem of a standard predicate calculus, then Defender wins provided the formula generated by the game is a theorem of the same standard predicate calculus augmented by the axioms for $\Box$.

Theorem 7.2. *Defender has a winning strategy on any theorem of a standard predicate calculus.*

Proof. All moves in the game consist in one of the players choosing a value of k and prefixing an atomic formula with $\Box^k$ for some k. Thus a strategy for either player is given by specifying, for each of his moves, the value of k to be played as a function of the values chosen by his opponent on all of the opponent's earlier moves.

We order strategies by saying that $S \leq S'$ if, at every play, for each choice of earlier moves by the opponent, the value of k prescribed by S' is greater than or equal to the value prescribed by S. We claim that if Attacker plays the same moves against two of Defender's strategies, S and S', such that $S \leq S'$, then the formula generated by the first game will imply the formula generated by the second game, and if Defender plays the same moves against two of Attacker's strategies, T and T', such that $T \leq T'$, then the formula generated by the first game will be implied by the formula generated by the second game. This is shown by a straightforward induction on the complexity of the formula on which the game is played, taking both claims for all simpler formulas as the induction hypothesis. It follows that any strategy greater than a winning strategy also wins.

The theorem can be proven using Gentzen-style sequent calculus. We work with the G1 systems of [3], using only atomic formulas in the axioms Ax and (in the intuitionistic and classical cases) replacing the axiom L$\perp$ with the axioms $\perp \Rightarrow A$ for all atomic formulas A. We first extend the definition of the game so that it can be played on sequents. On a sequent of the form $\Gamma, A \Rightarrow B, \Delta$ where Γ and Δ are the context, the game is played by having Attacker and Defender switch roles and play the game on the formulas of Γ in any order and then on A, then revert to their original roles and play the game on B and then, finally, on the formulas of Δ in any order. The proof is completed by checking that Defender has a winning strategy on any axiom, and if Defender has a winning strategy on the premises of a rule then he has a winning strategy on the conclusion of that rule. This is straightforward but tedious. In every case the strategy adopted by Defender on each formula in

the conclusion of a rule will be the strategy he used on the same formula in one of the premises of that rule. Since increasing a winning strategy always produces a winning strategy, if a formula appears in more than one premise we can assume that Defender played the same strategy in both cases. □

Say that a formula is *increasing* if no implication appears in the premise of any other implication. Note that since we take $\neg A$ to be an abbreviation of $A \to \bot$, this also means that an increasing formula cannot position a negation within the premise of any implication, nor can it contain the negation of any implication.

Corollary 7.3. *Suppose the nonlogical axioms of $\mathcal{T}_2$ are increasing and the nonlogical axioms of $\mathcal{T}_1$ are those of $\mathcal{T}_2$ with all boxes deleted. Then $\mathcal{T}_2$ weakly interprets $\mathcal{T}_1$.*

Proof. Let B be any theorem of $\mathcal{T}_1$. We must find a way to insert boxes into B so that it becomes a theorem of $\mathcal{T}_2$. Since $\mathcal{T}_1$ proves B, it is a logical consequence of finitely many nonlogical axioms A_i of $\mathcal{T}_1$; writing their conjunction as $A = \bigwedge A_i$ we then have that $A \to B$ is a theorem of a standard predicate calculus. The problem is to insert boxes into A and B, yielding new formulas A' and B', in such a way that $A' \to B'$ is a theorem of standard predicate calculus augmented by the axioms for $\Box$, and such that each conjunct A'_i of A' is implied by the corresponding nonlogical axiom A''_i of $\mathcal{T}_2$. It will then follow that B' is a theorem of $\mathcal{T}_2$, as desired.

We achieve this result by playing the game described above on the formula $A \to B$. We know that Defender can ensure that $A' \to B'$ is a theorem of standard predicate calculus augmented by the axioms for $\Box$, so all we need to do is to prescribe a strategy for Attacker which ensures that each conjunct A'_i of A' is implied by the axiom A''_i.

The game is played on $A \to B$ by first switching the players' roles and playing on A. So we reduce to a problem about finding a strategy for Defender when the game is played on A, and this amounts to giving a strategy for Defender on each conjunct A_i. We know that the formula A''_i is obtained from A_i by inserting boxes in some way, and we need to provide Defender with a strategy for playing the game on A_i in a way that ensures $A''_i \to A'_i$. We prove this can be achieved for any increasing formula A_i recursively on its complexity. The only interesting case is when A_i is an implication, $A_i = A_{i0} \to A_{i1}$. We require a lemma which states that if a formula C contains no implications and C' is obtained from C by inserting boxes in some way, then $C \to C' \to \Box^j C$ (i.e., $C \to C'$ and $C' \to \Box^j C$) for some value of j. This is easily shown by induction on the complexity of C. This lemma can be applied to A_{i0} because A_i is increasing, so no matter how the game is played on A_{i0} we will have $A'_{i0} \to \Box^j A_{i0} \to \Box^j A''_{i0}$ for some j. Inductively Defender can then employ a strategy on A_{i1} which ensures that $\Box^j A''_{i1} \to A'_{i1}$, and this yields that $A''_{i0} \to A''_{i1}$ implies

$$A'_{i0} \to \Box^j A''_{i0} \to \Box^j A''_{i1} \to A'_{i1},$$

that is, A''_i implies A'_i, as desired. □

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[2]See http://www.math.wustl.edu/∼nweaver/conceptualism.html